Bistability and pulsations in cw semiconductor lasers with a controlled amount of saturable absorption

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Experimental results of a buried heterostructure cw laser with a controllable amount of saturable absorption introduced by a segmented contact are presented. With no absorption the laser is stable and has a linear output characteristic. Increasing of the saturable absorption by changing the pump current through the control segment causes the light output of the device to pulsate and to show bistable and hysteretical behavior. The introduction of a controllable amount of saturable absorption suggest the usefulness of this device in generating extremely short pulses, for example, by passive mode locking and as a bistable optical device.

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Saturable absorbing defects are conjectured to play an important role in the dynamical behavior of semiconductor lasers. Some of the phenomena involved include mode locking,[1] self-pulsation,[2] and high-frequency modulation.

Unfortunately to date saturable absorption was not reliably controlled or even verified and short pulses were obtained only in lasers on the verge of failure. It is known from the analysis of dye lasers[3] that ultrashort pulses result when the radiation interacts with both a saturable absorber and a saturable gain if the saturation intensity of the loss is smaller than that of the gain. There are good reasons to believe that similar effects may play a role in mode-locked semiconductor lasers.[4]

More than a decade ago Lee *et al.*[5] observed that a diode laser with a tandem section produced a pulsating light output. Lately this double section scheme has been applied to a transverse junction stripe (TJS) structure[6] and resulted in optical pulses with a typical width of about 20 ps. This pulsating behavior is not expected from an otherwise well-behaved laser diode with a double-section contact, since the calculated gain dependence on the injected carrier concentration[7] does not seem to fulfill the above stated necessary condition for pulsation.

Earlier, Lasher[8] proposed a bistable injection laser based on the nonlinear absorption in a double-contact laser diode. Recently, Carney and Fonstad[9] operated a multiple segmented contact stripe laser and observed strong nonlinearities in the dc light current characteristic.

In this letter we present experimental results on pulsations and bistable behavior of a buried-heterostructure (BH) laser with a segmented contact as shown in Fig. 1. Threshold current for a uniformly pumped device, 250 μm in length, is typically 20 mA. The laser is made by a standard process.[10] A 25-μm-wide stripe is etched into the p-contact metallization before the wafer is cleaved into the single devices. The resistance between the two contact pads is measured to be around 1kΩ. Near- and far-field measurements show that the device lases over its complete operating range in the fundamental transverse mode. The use of the BH laser structure in this experiment thus makes it possible to isolate and study the effects of saturable absorption in the cw regime with a device whose optical and electronic behavior is stable and simple. The very low threshold current allows the device to be operated over a wide range of absorption in the control section.

The laser is operated with a constant current I_2 supplied to the control section (the segment which is 125 μm long). The light output is measured as a function of the pump current I_1 through the gain section. The cw light-current characteristics of the device are shown in Fig. 2 with I_2 as parameter. For $I_2 = 0$, the lasing threshold is about 27 mA, and the light-current-relation is linear up to an output power of about 4 mW per facet. This is not expected, since, with a zero pump current, the control section should act as a saturable

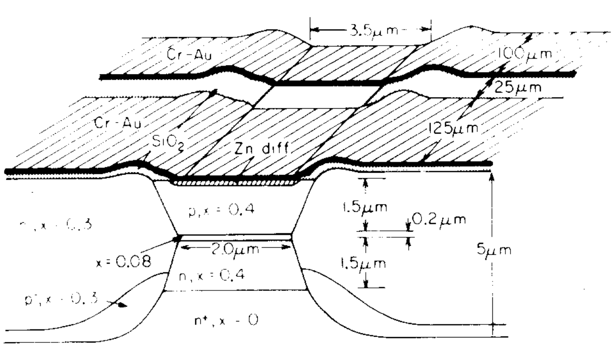

FIG. 1. Artist's view of the two-segment contact BH laser.

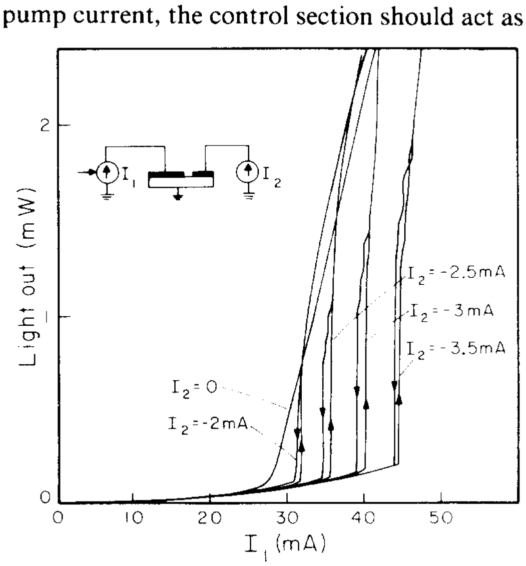

FIG. 2. Plot of the optical power output per mirror as a function of drive current I_1. Parameter is the current I_2 applied to the control section.

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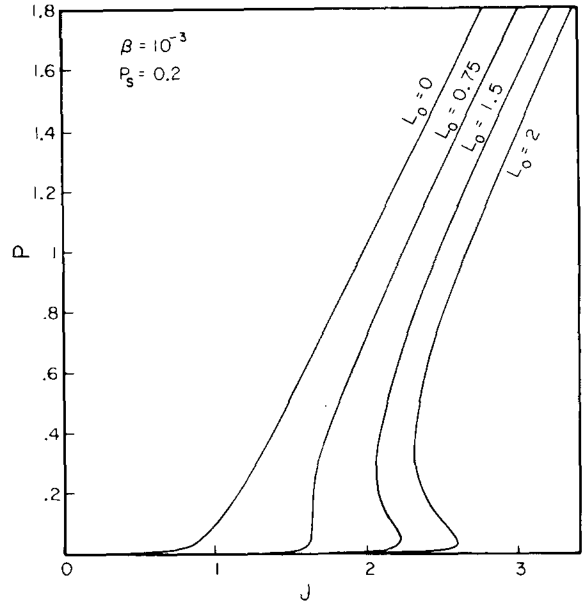

FIG. 3. Calculated light-current characteristics of a laser including saturable absorption.

absorber, and nonlinearites should result. The leakage current from the gain contact pad to that of the loss section cannot fully explain this fact, since the corresponding resistance is measured to be about 1 kΩ. A possible explanation is that the superluminescence below threshold is already intense enough to bleach the saturable absorption in the control section.

With $I_2 = -2$mA, however, nonlinearities result due to the increase of the saturable absorption; jumps and a hysteresis in the light-current characteristic are observed. With a further increase of the negative current I_2 to -3 mA and then to -3.5 mA through the control section, the light jumps become larger and the hysteresis becomes more pronounced. The threshold current of the device rises from 27 mA at no bias ($I_2 = 0$ mA) through the control section to about 45 mA for $I_2 = -3.5$ mA. These results are in qualitative agreement with the calculated dc light-current characteristic (Fig. 3) predicted by a model which includes a saturable photonloss term of the form $L_0/(1 + P/P_s)$ in the normalized rate equations.

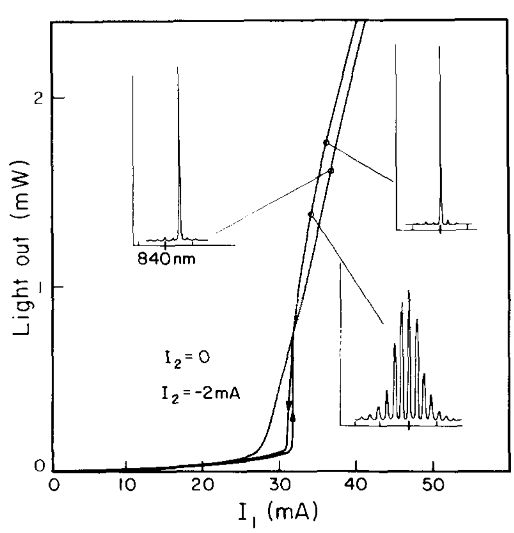

FIG. 4. Pulsing frequency as a function of the dc drive current I_1. Parameter is I_2 applied to the control contact. Δf is the pulsation linewidth.

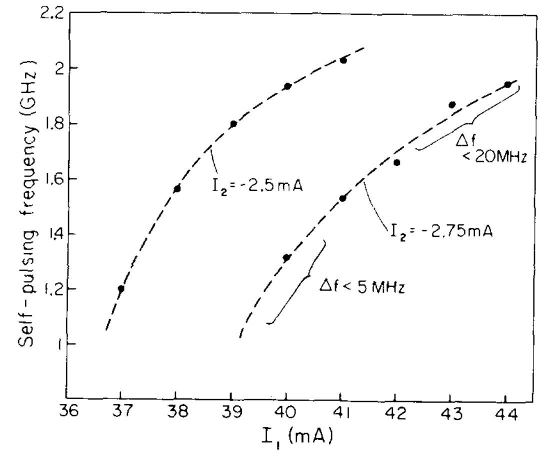

FIG. 5. Optical spectrum of the device at different operating points. The longitudinal mode spacing is 0.26 nm.

The microwave fluctuation spectrum of the detected light was observed with a spectrum analyzer. With the control section unpumped ($I_2 = 0$ mA), the device was stable and did not pulsate. However with $I_2 \leqslant -2$ mA the laser became unstable. It was observed that pulsation occurs in a pumping region above threshold. The pulsing frequency increases as the current through the gain section is increased, in a manner similar to a typical pulsing laser, as shown in Fig. 4. At very high pumping levels (e.g. $I_1 = 42$ mA for $I_2 = -2$ mA) the self-pulsation disappears and the laser became stable again. The linewidth of the microwave spectrum increases from 5 MHz just above the light jump to about 20 MHz at higher pumping levels. Near the light jumps the microwave spectrum consisted of a very narrow-band oscillation with a frequency of 610 MHz for different currents through the control section. The fact that at a given pump current I_1 the output power for $I_2 = -2$ mA can exceed that for $I_2 = 0$ mA, as shown in Fig. 2, could be explained on the basis that in a pulsating laser the inversion can swing well below the critical (dc) value, thus resulting in an increased rate of stimulated emission.

The optical spectrum consisted of a single longitudinal mode for $I_2 = 0$ mA, but changed to a large number of broadened lines when I_2 was increased to a value where hysteresis and light jumps are observed. The emission width in this regime is about 2 nm. Above the light jump the emitted spectrum narrowed, and far above the jump the device was lasing in a single mode as shown in Fig. 5. Measurements of the near- and far-field showed that the laser was operating under all conditions in the fundamental mode, demonstrating the effectiveness of the BH waveguiding structure.

The introduction of a controllable amount of saturable absorption suggests the usefulness of this device in generating extremely short optical pulses, for example, by passive mode locking and as a bistable optical element.

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Optical frequency shifting lever

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Multiplication of the frequency shift of a tunable solid-state laser is achieved via resonant pumping in a double-doped rare-earth crystal. With a tuning shift of only 0.6 nm of the pump, an output shift of 100 nm is achieved.

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High peak power multiple frequency lasers are of interest for an increasing variety of applications. Most high-performance lasers, however, emit in a single, relatively narrow frequency range. Recent work has shown that resonant pumping of rare-earth-activated crystalline lasers can be employed to shift the frequency of a pump laser (linear down conversion), extending the applicability of high-performance lasers. Efficient frequency conversion of XeF lasers in Tm:YLF,[1] KrF in Ce:YLF,[2] doubled Nd:glass in Ho and Er:YLF,[3] and doubled Nd:YAG in Ho and Er:YLF (Ref.4) have been demonstrated. Knights *et al.*[4] have further shown that linear down conversion can provide high conversion efficiencies and very high average power densities. In this letter we describe a resonant pumped rare-earth laser system in which large frequency shifts are generated at the output with relatively small frequency shifts in the pump laser.

Wavelength diversity in lasers can be obtained by tuning over the gain curve of the active medium or by frequency shifting the narrow line laser output in a linear or nonlinear converter. Frequency "tuning" techniques generally employ some dispersive element to produce a variable wavelength-dependent loss. Frequency shifting techniques include linear down conversion processes such as resonantly pumping solid or dye lasers and nonlinear processes such as harmonic generation, mixing, parametric amplification, and stimulated Raman scattering. Several of these techniques also provide tunable outputs. Nonlinear shifting techniques coupled with a tunable laser pump can multiply the frequency shift of the pump. For example, the tunable second-harmonic generation range is double the tuning range of the pump laser. However, throughout the tuning range the shifted frequency provided by the nonlinear process has a direct dependence on the pump laser frequency.

In linear down conversion the shifted frequency depends only on the energy level structure of the converting medium. Generation of stimulated emission from an excited state to any of a series of lower lying states is obtained by providing feedback at the appropriate wavelength and losses at competing transitions. It is also possible, in principle, to address different excited states by appropriately changing the frequency of the pump source. With rare-earth-activated solids this would require rather large pump frequency shifts in the case of single-doped systems. This is because pump frequency shifts that are smaller than the total Stark splitting of a J multiplet (a few hundred wave numbers) would not shift the output wavelength, since the Stark levels are rapidly thermalized.

In multiple-doped systems, however, near-resonant metastable states in different ions exist. Resonant or near-resonant transfer rates between different rare-earth ions are much slower[5] than the relaxation rates between Stark levels of a J multiplet of one ion. Therefore for durations shorter than the transfer time, near-resonant levels are effectively populated only by the pump source. Such states will therefore maintain separate identities in the different ions. In such a system a small change in the pump frequency addresses a totally different series of energy states with a new set of selectable laser transitions.

The $^5F_4$, $^5S_2$, and $^2H_{11/2}$, $^4S_{3/2}$ multiplets of Ho- and Er-doped YLF are an example of such a system. These closely spaced manifolds in each activator ion are separately in thermal equilibrium. In spite of the near resonance of these states the transfer time between them is rather long. For example, in a 2% Ho, 2% Er crystal the transfer rate between the ions